FESHM 4240: OXYGEN DEFICIENCY HAZARDS (ODH)

Revision History

Author	Description of Change	Revision No. & Date
Richard Schmitt	1. Revised Table 2 failure rates for fans and louvers and added references 2. Added Technical Appendix 4- Standby Ventilation Equipment Failure on Demand Rates and Sample Calculations 3. Case E, stratification of gases is redefined 4. Table 6, duration of approval changed 5. Added contractors to approval procedures 6. Removed references to ODH approval cards 7. Table 5, added area monitoring and notes.	January, 2015
Richard Schmitt	1. Revised Table 2 failure rates for flanges, piping, valves and vessels. Added source references for each failure mode 2. Spelled out abbreviations in Table 2 3. Clarified escort rules in Table 5 4. Removed ODH approval card 5. Reaffirmed Table 1 values	June, 2012
Bill Cooper	1. Reconcile with OSHA 19.5% 2. Invoked ALARA principal 3. Augmented definitions 4. Required Div. Heads to maintain records 5. Required all areas to be class 2 or lower 6. Modified procedures per safety training booklet 7. Addressed entry into unusual oxygen deficiency hazards 8. Addressed underground installations 9. Revised introduction to include ALARA 10. Clarified that ODH is based on fatality 11. Reformatted equations 12. Eliminated classes 3 and 4	May, 2009

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INTRODUCTION

The use of compressed and liquefied gases is commonplace at Fermilab. The introduction of these materials to the atmosphere can present a hazard. In particular, persons exposed to reduced-oxygen atmospheres may experience reduced abilities, unconsciousness, or death. The purpose of this chapter is to specify requirements for assessing the potential for and controlling hazards associated with a possible oxygen deficient environment. This chapter does not address the general topic of confined spaces (see Chapter 4230 and definition of "ODH operation" below).

APPLICABLE STANDARDS

American Conference of Governmental Industrial Hygienists (ACGIH) 2005 Threshold Limit Values (TLVs) for Chemical Substances and Physical Agents & Biological Exposure Indices (BEIs) – Minimal Oxygen Content

DEFINITIONS

ALARA (As Low As Reasonably Achievable) - The approach to protection from hazards by managing and controlling exposure to potential hazards (both individual and collective) to the work force and to the general public at levels as low as is reasonable, taking into account social, technical, economic, practical and public policy considerations. As used in this Manual, ALARA is not a hazard limit but a process which has the objective of reducing hazards as far below the applicable limits as is reasonably achievable.

mmHg - a unit of measure of pressure based upon a liquid mercury column. The pressure exerted by gravity at the base of a liquid mercury column n mm tall is n mmHg.

ODH Monitor - a device, usually permanently attached to a structure, which monitors the concentration of oxygen and alarms at a set value. ODH monitors must be set to alarm at 18% oxygen or higher and can be used to activate other systems.

Operations - activities, which are performed in a specific area or location. Operations include simply being in a specific location.

Oxygen concentration - the molar fraction of a gaseous mixture represented by oxygen. For a mixture of ideal gases, it is also equal to the ratio of the partial pressure of oxygen to the total mixture pressure. The oxygen concentration in normal ambient atmosphere is 20.9% (~21%).

Oxygen deficiency - any condition under which the partial pressure of atmospheric oxygen is less than 144 mmHg (about 19.5% by volume at a barometric pressure of 740 mmHg at Fermilab).

Oxygen deficient area - any area known to have an oxygen deficiency.

Oxygen deficiency hazard (ODH) operation - an operation which exposes personnel to an increased risk of fatality in excess of 10^{-7}/hr due to oxygen deficiency. Unlike confined spaces, ODH work spaces are generally designed for occupancy and provided with normal building-type access and egress. In addition, the hazard is primarily limited to oxygen deficiency which is well understood and controlled through quantitative risk assessment.

Partial pressure - the pressure due to one of several components of a gaseous mixture. For a mixture of ideal gases, the sum of component partial pressures equals the mixture pressure.

Personal Oxygen Monitor - a device carried by an individual that monitors the concentration of oxygen and alarms at a set value. All personal Oxygen Monitors used at Fermilab are set to alarm at the mandatory confined space limit of 19.5% (see Chapter 4230).

SCBA (Self-Contained Breathing Apparatus) - a device worn by rescue workers, firefighters, and others to provide breathable air in a hostile environment. An SCBA typically has three main components: a high-pressure tank (*e.g.,* 2200 psi to 4500 psi), a pressure regulator, and an inhalation connection (mouthpiece, mouth mask or face mask), connected together and mounted to a carrying frame.

Self-Rescue supplied atmosphere respirator (escape pack) - a device containing breathing air to be used for escape during an ODH event. Such a device normally provides an air supply which lasts approximately five minutes and is to be used for escape only.

SPECIAL RESPONSIBILITIES

Division/Section heads or their designees have the responsibility of implementing the requirements of this chapter. This includes appointment of qualified persons to review, approve, and maintain documentation for ODH risk assessments under the control of their organizations; maintain records of reliability of ODH-associated equipment; and maintain records of incidents which have resulted in an oxygen deficient atmosphere.

The ESH&Q Section has the responsibility for the purchase and maintenance of personal oxygen monitors and the provision of standardized warning signs as described in the Technical Appendix to this document. In addition, the Medical Department is responsible for reviewing the medical fitness of persons who participate in ODH operations.

The Cryogenic Safety Subcommittee and/or the Mechanical Safety Subcommittee serve division/section heads and the ESH&Q Section in a consulting capacity on ODH risk assessment issues.

The Industrial Hygiene Subcommittee provides oversight and consulting on the technologies and procedures for monitoring oxygen deficient atmospheres.

PROCEDURES

1. A quantitative assessment of the increased risk of fatality from exposure to reduced atmospheric oxygen shall be conducted for all operations~~,~~ which are physically capable of exposing individuals to an oxygen deficiency. This assessment shall assign an Oxygen Deficiency Hazard Class to each area with potential risk as well as specify any unusual precautionary requirements. The classification of an area can change depending on the operations being performed. If conditions and/or activities change in ways that significantly increase the risk, the associated quantitative assessment must be accordingly revised. The technical appendix entitled "ODH Risk Assessment" is to be used in carrying out the assessment.

2. Control measures appropriate to the ODH Class shall be implemented as stated in the risk assessment and Technical Appendix. ODH Class 0 is the least hazardous. ODH Class 2 is the most hazardous. The technical appendix entitled "ODH Control Measures" is to be followed to control the potential ODH hazard.

3. Equipment at Fermilab shall be designed and installed (engineered) to ensure that areas intended for human entry during normal operation will be ODH Class 0, ODH Class 1, or ODH Class 2. No area intended for human entry during normal operation will be engineered for an ODH Class higher than 2. For Confined Space requirements (not under the scope of this chapter), see Chapter 4230.

   3.1. If an area cannot be engineered to satisfy requirements leading to an ODH Class of 2 or lower, the Division/Section Head responsible for the area must submit a written exception request to the Director or Director's designee. The request should include a justification and an evaluation of hazards, procedures, and safety measures. The request must be approved by the Director or designee before operations contributing to oxygen deficiency hazards are begun.

4. The ALARA principle shall be applied. Occupancy of areas with oxygen deficiency hazards should be limited to the extent practical while still allowing work to be performed expeditiously. Work in such areas should be planned to minimize the duration of occupancy. Offices should not be located in areas with oxygen deficiency hazards.

5. Divisions/Sections should maintain records of reliability of ODH-associated equipment and records of ODH alarms that were the result of an oxygen deficient atmosphere. These data should be periodically reviewed by the Cryogenic Safety Subcommittee to improve failure rate estimates such as those included in the Technical Appendix to this chapter.

6. Response to an alarm from a personal oxygen monitor:

   6.1. If one person is working alone in an area and his/her personal oxygen monitor alarms, the person must immediately don a self-rescue supplied atmosphere respirator (escape pack), evacuate the area, and dial 3131 to report an emergency.

   6.2. If two or more people are working together in an area and a personal oxygen monitor alarms, they should compare readings. If other monitors read OK, then everyone must evacuate the area and solve the problem with the personal oxygen monitor before re-entering. If other monitors confirm low oxygen levels, then everyone must don an escape pack, evacuate the area, and then dial 3131 to report an emergency.

7. Response to an alarm from an in-place oxygen monitor:

   7.1. If one person is working alone in an area and an in-place oxygen monitor alarms, and his/her personal oxygen monitor reads greater than 19.5%, the person should evacuate the area going away from the assumed source of the alarm. After exiting, he/she should notify the operations department responsible for the area of the problem. He/she should not re-enter until the problem has been solved. If a personal oxygen monitor has alarmed as well, the procedure of 6.1 should be followed.

   7.2. If two or more people are working together, they should compare readings of personal oxygen monitors. If all personal oxygen monitors read OK, everyone should evacuate the area going away from the assumed source of the alarm. After evacuating, they should notify the operations department responsible for the area of the problem. They should not re-enter the area until the problem has been solved. If a personal oxygen monitor confirms low oxygen levels, everyone should don an escape pack, evacuate the area, and then dial 3131 to report an emergency.

8. Response to other indications of a possible cryogen or gas leak (vapor cloud, sound of gas leak, etc.):

   8.1. If one person is working alone and his/her personal oxygen monitor reads greater than 19.5%, he/she should evacuate the area going away from the assumed source of the problem. After exiting, he/she should notify the operations department responsible for the area of the problem. If a personal oxygen monitor has alarmed, he/she must immediately don a self-rescue supplied atmosphere respirator (escape pack), evacuate the area, and dial 3131 to report an emergency.

   8.2. If two or more people are working together, they should compare personal oxygen monitor readings. If all are OK, they should all evacuate the area going away from the assumed source of the problem. After exiting, they should notify the operations department responsible for the area of the problem. If a personal oxygen monitor has alarmed, they must immediately don self-rescue supplied atmosphere respirators (escape packs), evacuate the area, and dial 3131 to report an emergency.

9. Entry into an area with unusual oxygen deficiency hazards:

   9.1. Any rescue must be conducted by emergency (Fire Department) personnel. If an area is suspected to be oxygen deficient or to present an elevated risk for oxygen deficiency hazards, an unexposed observer and the use of SCBA equipment are required. Training and medical approval are required for the use of SCBA equipment.

   9.2. If, for purposes other than rescue, entry must be made into an oxygen deficient area or an area suspected to present an elevated risk for oxygen deficiency hazards, the Division/Section Head responsible for the area must submit a written request to the Director or Director's designee which includes a justification and outlines hazards, procedures, and safety measures. The request must be approved by the Director or designee before entry.

10. In general, ODH evaluation procedures and measures to address hazards in underground installations are the same as those required for surface installations. However, time of egress may be longer, inerting gases or cryogenic fluids may

accumulate, and rescue operations may be more difficult. All of these factors must be taken into account in analyses and protective measures.

10.1. If there are oxygen deficiency hazards and normal entry and egress is by means other than by foot, at least one egress path to a “safe area” which can be reached by foot must be provided. The safe area must be free of oxygen deficiency hazards and remain so during all plausible equipment failures. If the safe area relies upon ventilation, emergency power must be provided to its ventilation systems.

10.2. The path to the safe area must be adequately marked and illuminated and remain free of obstructions during plausible ODH incidents.

10.3. A written plan for evacuation of personnel from the safe area to the surface must be prepared and approved.

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TECHNICAL APPENDIX

1. **ODH RISK ASSESSMENT**

The ALARA principle is to be applied to all areas with oxygen deficiency hazards. Any area known to have an oxygen concentration <19.5% is considered to be an oxygen deficient area. All areas intended for human occupancy at Fermilab shall have an environment or environmental controls which will normally ensure that the concentration of oxygen remains above19.5%. If an area contains equipment or sources of inert gas which could lead to a significant decrease in oxygen concentration, additional measures shall be taken to reduce risk to personnel. The goals of an ODH risk assessment are to evaluate the level of risk in a given area, to classify the area based upon the level of risk, that is, to assign an ODH Class to the area, and to specify additional safety measures to be taken to reduce risks. The ODH risk assessment should be documented, reviewed, and approved.

The ODH Class is based upon the most severe risk: the likelihood that a fatality will occur. Since the level of risk is tied to the area and the nature of the operation, the fatality rate shall be determined on an operation-by-operation basis. For a given area and operation several events may cause an oxygen deficiency. Each event has an expected rate of occurrence and each occurrence has an expected probability of causing a fatality. The oxygen deficiency hazard fatality rate is defined as:

$$\phi = \sum_{i=1}^{n} P_i F_i$$

where ϕ = the ODH fatality rate (per hour),

P_i = the expected rate of the i^{th} event (per hour), and

F_i = the probability of a fatality due to event i.

The summation shall be taken over all events which may cause oxygen deficiency and result in fatality. When possible, the value of P_i shall be determined by operating experience at Fermilab; otherwise data from similar systems elsewhere or other relevant values shall be used. Estimates of equipment failure rates are given in

Table 1 and Table 2.

Table 1 contains median estimates collected from past ODH risk assessments at Fermilab (see Technical Appendix Section 3). Table 2 contains values derived from the nuclear power industry and industrial records. Human error rate estimates are presented in Table 3.

The risk assessment should also consider the benefit of existing active control systems such as forced ventilation or any supply shut-off valves which are automatically activated by area monitor readings or system failure indicators. These systems must be designed to be activated before the area drops below 18% oxygen concentration. Although such systems or any forced ventilation system reduces overall risk, they are also subject to failure and this shall be factored into the risk assessment. This is accomplished by summing the expected failure rate of all systems and the corresponding fatality factors for when those systems have failed. For example, a fan which is triggered by a low oxygen monitor reading may not function properly because of a power failure, inadequate maintenance, or the monitor's calibration drifting. Therefore, the probability that these failures will occur and compromise the ventilation system shall be factored into the overall risk assessment. Also, since the ϕ calculation for defining ODH hazard is based on untrained personnel using no special personal protection, the risk assessment must assume that personnel take no direct action in responding to ODH conditions. For example, ϕ cannot be reduced by assuming a person hearing an alarm will exit.

The value of F_i is the probability that a person will die if the i^{th} event occurs. The value depends on the oxygen concentration. For convenience of calculation, an approximate relationship between the value of F_i and the lowest attainable oxygen concentration has been developed (Figure 1). The lowest attainable concentration is used, rather than an average, since that minimum value is conservative and the time dependence of the concentration is normally not well known. If the lowest oxygen concentration is greater than 18%, then the value of F_i is zero, that is, all exposures above 18% are defined to be "safe" and to not contribute to fatality. It is assumed that all exposures to 18% oxygen or lower do contribute to fatality and the value of F_i is designed to reflect this dependence. If the lowest attainable oxygen concentration is 18%, then the value of F_i is 10^{-7}. This value would cause ϕ to be 10^{-7} per hour if the expected rate of occurrence of the event were 1 per hour. At decreasing concentrations, the value of F_i should increase until, at some point, the probability of fatality becomes unity. That point was selected to be 8.8% oxygen, the concentration at which one minute of consciousness is expected.

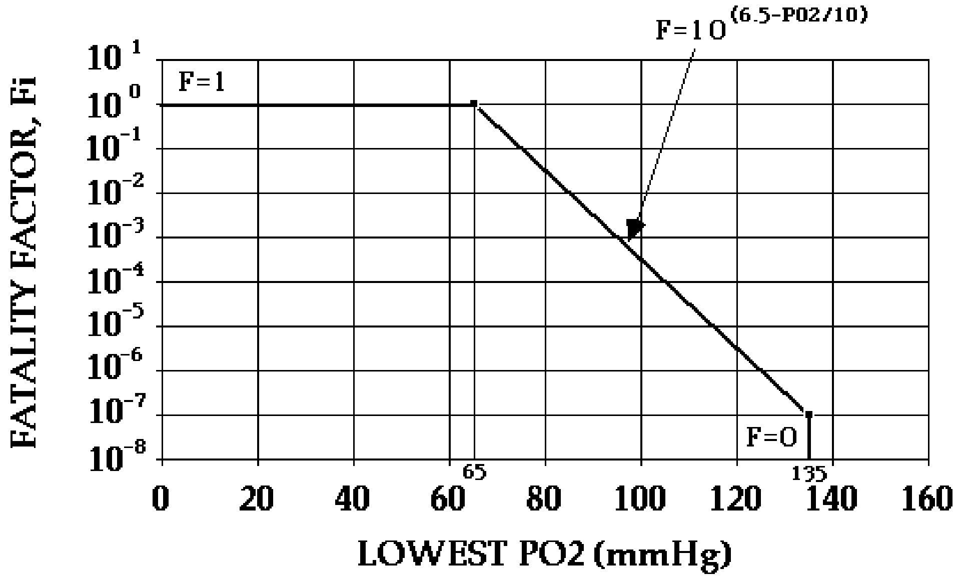


Figure 1, Fatality Factor

Graph of the logarithm of the fatality factor (Fi) versus the lowest attainable oxygen concentration which can result from a given event. This relationship should be used when no better estimate of the probability of fatality from a given event is available.

Table 1, Fermilab Equipment Failure Rate Estimates

System	**Failure Mode**	**Failure Rate**
Compressor (Two-stage Mycom)	Leak Component rupture	5×10^{-6}/hr 3×10^{-7}/hr
Dewar	Loss of vacuum	1×10^{-6}/hr
Electrical Power Failure (unplanned)	Time Rate Demand Rate Time Off	1×10^{-4}/hr 3×10^{-4}/D 1 hr
Fluid Line (Cryogenic)	Leak Rupture	5×10^{-7}/hr 2×10^{-8}/hr
Cryogenic Magnet (Powered, unmanned)	Rupture	2×10^{-7}/hr
Cryogenic Magnet (Not powered, manned)	Rupture	2×10^{-8}/hr
Header Piping Assembly	Rupture	1×10^{-8}/hr
U-Tube Change (Cryogen Release)	Small Event Large Event	3×10^{-2}/D 1×10^{-3}/D

Table 2, Equipment Failure Rate Estimates

	Failure Mode	Median Failure Rate	Source
BATTERIES, POWER (UPC) SUPPLIES	No output	3x10-6/HR	a
CIRCUIT BREAKERS	Failure to Operate	1x10-3/D	a
	Premature Transfer	1x10-6/HR	a
DIESEL			
(Complete Plant)	Failure to Start on Demand	3x10-2/D	a
(Emergency Run Loads)	Failure to Run	3x10-3/HR	a
(Engine Only)	Failure to Run	3x10-4/HR	a
FANS	Failure to Run	$9x10^{-6}$/HR	i
(fan, motor & starter)	Failure to start on demand	see Technical App.4	
	Fans with Variable Frequency Drive see footnote k		
FUSES	Premature, Open	1x10-6/HR	a
	Failure to Open	1x10-5/D	a
FLANGES			
With Reinforced & Preformed Gaskets	Leak, 10 mm^2 opening	$4x10^{-7}$/HR	c,d
	Rupture	$1x10^{-9}$/HR	c,d
FLANGES			
With packing or soft gaskets	Leak, 10 mm^2 opening	$4x10^{-7}$/HR	c,d
	Packing Blowout	$3x10^{-8}$/Hr	c
	Rupture	$1x10^{-9}$/HR	c,d
INSTRUMENTATION	Failure to Operate	1x10-6/HR	a

	Shifts	3x10-5/HR	a
(Amplification Transducers, Calibration, Combination)			
MOTORIZED LOUVER	failure in continuous operation	$3x10^{-7}$/HR	j
	failure to open on demand	See Tech. App. 4	
PIPING	small leak, $10mm^2$	$1x10^{-9}$/meter-HR	c
	pipes>2”, large leak, $1000mm^2$	$1x10^{-10}$/meter-HR	c
	Rupture	$3x10^{-11}$/meter-HR	c
PIPE Welds	small leak, $10mm^2$	$2x10^{-11}$*(D/t)/HR	c,e
D=Diameter	pipes>2”, large leak, $1000mm^2$	$2x10^{-12}$*(D/t)/HR	c,e
t=wall thickness	Rupture	$6x10^{-13}$*(D/t)/HR	c,e
PUMPS	Failure to Start	1x10-3/D	a
	Failure to Run – Normal	3x10-5/HR	a
	Failure to Run - Extreme Env.	1x10-3/HR	a
RELAYS	Failure to Energize	1x10-4/D	a
	Failure NO Contact to Close	3x10-7/HR	a
	Short Across NO/MC Contact	1x10-8/HR	a
	Open NC Contact	1x10-7/HR	a
SOLID STATE DEVICES			
HI PWR application	Fails to Function	3x10-6/HR	a
	Shorts	1x10-6/HR	a
Low PWR application	Fails to Function	1x10-6/HR	a
	Shorts	1x10-7/HR	a
SWITCHES	Limit: Failure to Operate	3x10-4/D	a
	Torque: Fail to OPER	1x10-4/D	a
	Pressure Fail to OPER	1X10-4/D	a
	Manual, Fail to TRANS	1x10-5/D	a
	Contacts Shorts	1x10-8/HR	a

TRANSFORMERS	Open CKT	1x10-6/HR	a
	SHORT	1x10-6/HR	a
VALVES, Motor operated	Fails to Operate (Plug)	1x10-3/D	a
	Failure to Remain Open	1x10-4/D	a
	External Leak	$1x10^{-8}$/HR	c,f
	Rupture	$5x10^{-10}$/HR	c,f
VALVES, Solenoid operated	Fails to Operate	1x10-3/D	a
VALVES, Air operated	Fails to Operate (Plug)	3x10-4/D	a
	Failure to Remain Open	1x10-4/D	a
	External Leak	$1x10^{-8}$/HR	c,f
	Rupture	$5x10^{-10}$/HR	c,f
VALVES, Check	Failure to Open	1x10-4/D	a
	Reverse Leak	3x10-7/HR	a
	External Leak	$1x10^{-8}$/HR	c,f
	Rupture	$5x10^{-10}$/HR	c,f
VALVES: Orifices, Flow Meters, (Test)	Rupture	1x10-8/HR	a
VALVES, Manual	Failure to Remain Open (Plug)	1x10-4/D	a
	External Leak	$1x10^{-8}$/HR	c,f
	Rupture	$5x10^{-10}$/HR	c,f
VALVES, Relief	Fail to Open/D	1x10-5/D	a
	Premature Open/HR	1x10-5/HR	a
Vessels, Pressure	Small leak, $10mm^2$	$8x10^{-8}$/HR	b,g,h
	Disruptive Failure	$5x10^{-9}$/HR	b,g,h

WIRES	Open	3x10-6/HR	a
	Short to GND	3x10-7/HR	a
	Short to PWR	1x10-8/HR	a

References

a) Legacy value, may be from NRC tables

b) Lees, Frank. *Loss Prevention in the Process Industries*, 1996. Print. page 12/97, and Engel, J.R. "Pressure Vessel Failure Statistics and Probabilities" *Nuclear Safety*, Vol. 15, No. 4 (1974): 387-399. Leak size based on possible crack size as the most common type of vessel failure.

c) Taylor, J.R. *Risk Analysis for Process Plant, Pipelines and Transport*. 1994. Print.

d) Blanton, C.H. and Eide, S.A. *Savannah River Site Generic Data Base Development*, WSRC-TR-93-262, June 1993. page 22. Westinghouse Savannah River Company, <http://www.osti.gov/bridge/servlets/purl/ 10136712tpHUgx/native/10136712.pdf>.

e) Most references include pipe weld failures in the per meter failure rates. Fullwood quotes Thomas that since most failures occur at welds the he finds a weld failure rate as a function of pipe diameter and wall thickness. Unfortunately Thomas does not state a physical basis for his equation, according to Fullwood.

f) Eide, S.A. et al., *Generic Component Failure Data Base for Light Water and Liquid Sodium Reactor PRAs*, February 1990. EGG-SSRE-8875, Idaho National Engineering and Environmental Laboratory, Idaho Falls, ID.

g) Davenport, T.J. "A Further Study of Pressure Vessel Failures in the UK." *Reliability '91*. Ed. R.H. Matthews., table 5, page 96, quoting Smith & Warwick, include a 95% confidence factor. Note that Davenport includes air receivers, yet has a lower failure rate than Arulanantham and Lees.

h) Smith, T.A. and Warwick, R.G., "Survey of Defects in Vessels Built to High Standards",*Int. J. Pres. Ves. & Piping* (2) (1974):283-322. Referring to conventional vessels relevant to Nuclear power plant, page 321

i) AICHE, "Guidelines for Process Equipment Reliability Data" with references to

   a. IEEE Standard 500-1984

   b. Offshore Reliability Data Handbook

   c. RADC Non Electronic reliability notebook, Rome Air Development Center

d. Reactor Safety Study (WASH 1400)

j) Eide, "Generic Component Failure Data Base", Table 3, referring to dampers

k) Fans with variable frequency drives may use the same failure rates as fans with on/off control if installed properly. Proper installation includes adequate cooling, appropriate wire sizes and possibly reactors. Proper installation must be documented with a signed engineering note and/or a signed engineering drawing.

Table 3, Human Error Rate Estimates

Est Error Rate (D^{-1})	Activity
10^{-3}	Selection of a switch (or pair of switches) dissimilar in shape or location to the desired switch (or pair of switches), assuming no decision error. For example, operator actuates large handled switch rather than small switch.
3×10^{-3}	General human error of commission, e.g., misreading label and therefore selecting wrong switch.
10^{-2}	General human error of omission where there is no display in the control room of the status of the item omitted, e.g., failure to return manually operated test valve to proper configuration after maintenance.
3×10^{-3}	Errors of omission, where the items being omitted are embedded in a procedure rather than at the end as above.
1/x	Given that an operator is reaching for an incorrect switch (or pair of switches), he selects a particular similar appearing switch (or pair of switches), where x = the number of incorrect switches (or pair of switches) adjacent to the desired switch (or pair of switches). The 1/x applies up to 5 or 6 items. After that point the error rate would be lower because the operator would take more time to search. With up to 5 or 6 items he doesn't expect to be wrong and therefore is more likely to do less deliberate searching.
10^{-1}	Monitor or inspector fails to recognize initial error by operator. Note: With continuing feedback of the error on the annunciator panel, the high error rate would not apply.
10^{-1}	Personnel on different work shift fail to check condition of hardware unless required by check or written directive.
5×10^{-1}	Monitor fails to detect undesired position of valves, etc., during general walk-around inspection, assuming no check list is used.
0.2 - 0.3	General error rate given very high stress levels where dangerous activities are occurring rapidly.
$2^{(n-1)}x$	Given severe time stress, as in trying to compensate for an error made in

an emergency situation, the initial error rate, x, for an activity doubles for each attempt, n, after a previous incorrect attempt, until the limiting condition of an error rate of 1.0 is reached or until time runs out. This limiting condition corresponds to an individual's becoming completely disorganized or ineffective.

A. ODH Assessment Equations

The oxygen concentration in a confined volume during and after a release of an inert gas may be approximated with the following equations. Five Different cases are presented:

Case A. During release, with perfect mixing- Ventilation fan(s) blowing into the confined volume.

Case B. During release, with perfect mixing - Ventilation fan(s) drawing from the confined volume with the ventilation rate greater than the spill rate.

Case C. During release, with perfect mixing - Ventilation fan(s) drawing from the confined volume with the ventilation rate less than or equal to the spill rate.

Case D. After release, with perfect mixing.

Case E. Stratification of inerting gases

The equation and its solution are given which are based on an oxygen mass balance for the confined volume. The following definitions and assumptions are common for each case:

Definitions

C = oxygen concentration

Cr = oxygen concentration during the release

Ce = oxygen concentration after the release has ended

Q = ventilation rate of fan(s), (cfm or m^3/s)

R = spill rate into confined volume, (scfm or m^3/s)

t = time, (minutes or seconds) beginning of release is at t=0

t_e = time when release has ended, (minutes or seconds)

V = confined volume, (ft^3 or m^3)

Assumptions

* For case A through D complete and instantaneous mixing takes place in the confined volume. This is only a good assumption where gases have similar densities and/or mixing is "vigorous."

* Q, R, and V remain constant.

* Pressure in the confined volume remains constant and very near atmospheric pressure through the use of louvers or natural leakage.

* Gas entering from outside the confined volume is air with an oxygen concentration of 0.21 (21%).

Case A During release - Ventilation fan(s) blowing outside air into the confined volume. Differential equation for the oxygen mass balance

$$V\frac{dC}{dt} = 0.21Q - (R+Q)C \quad (1)$$

Solution with the boundary condition of C=0.21 at t=0

$$C(t) = \left(\frac{0.21}{Q+R}\right)\left[Q + R\, e^{-\left(\frac{Q+R}{V}\right)t}\right] \quad (2)$$

Case B During release - Ventilation fans(s) drawing contaminated atmosphere from the confined volume with the ventilation rate greater than the spill rate (Q>R).

Differential equation for the oxygen mass balance

$$V\frac{dC}{dt} = 0.21(Q-R) - QC \quad (3)$$

Solution with the boundary condition of C=0.21 at t=0

(4) $$C(t) = 0.21\left(1 - \frac{R}{Q}\left(1 - e^{-\frac{Q}{V}t}\right)\right)$$

<u>Case C</u> During release - Ventilation fans(s) drawing contaminated atmosphere from the confined volume with the ventilation rate less than or equal to the spill rate ($Q \leq R$).

Differential equation for the oxygen mass balance

(5) $$V\,\frac{dC}{dt} = -\,R\,C$$

Solution with the boundary condition of C = 0.21 at t = 0

(6) $$C(t) = 0.21\,e^{-\frac{R}{V}t}$$

<u>Case D</u> After release - The oxygen concentration in the confined volume after the release has ended, $C_e(t)$, can be approximated by one equation.

Differential equation for the oxygen mass balance

(7) $$V\,\frac{dC}{dt} = 0.21\,Q - Q\,C$$

Solution with the boundary condition of $C = C_r\,(t_e)$ at $t = t_e$

(8) $$C(t) = 0.21 - \left[0.21 - C_r(t_e)\right]e^{-\frac{Q}{V}(t - t_e)}$$

where $(t - t_e)$ is the time duration since the release ended.

Oxygen concentrations can be converted to partial pressures by:

(9) $$PO_2 = C\,P_a$$

where C = oxygen concentration

PO_2 = oxygen partial pressure (mmHg)

P_a = atmospheric pressure (mmHg)

(~ 740 mmHg at Fermilab)

Case E Stratification of gases - The effects of stratification must be considered. The oxygen concentration can vary depending on distance from the release, elevation, gas density, ventilation, time and other factors. In most cases simple, conservative assumptions regarding mixing are more suitable than attempting a precise evaluation of mixing. For large enclosures it may be reasonable to assume complete mixing in a portion of the volume. Stratification should not be used to reduce the risk.

B. ODH Hazard Classes

Once the ODH fatality rate (ϕ) has been determined, the operation shall be assigned an ODH class according to Table .

Table 4, Oxygen Deficiency Hazard Class

ODH Class	[ϕ] (hr^{-1})
0	$<10^{-7}$
1	$> 10^{-7}$ but $<10^{-5}$
2	$> 10^{-5}$ but $<10^{-3}$

Please note that areas intended to be entered by personnel during normal operations must be engineered to have an ODH Class of 2 or lower.

An ODH risk assessment should include a discussion of each of the following:

1. Significant potential sources of reduced oxygen
2. Mechanisms
   - A. Spontaneous failures
   - B. Personnel-mediated failures
     - i) Operator error
     - ii) Accidents
3. Operations
   - A. Steady State
   - B. Other
     - i) Start up
     - ii) Repairs
     - iii) Special operations
     - iv) Shutdown
4. Gas dynamics
   - A. Ventilation
     - i) Natural
     - ii) Forced
   - B. Stratification/Mixing
   - C. Diffusion
5. The bases used for conclusions.

2. ODH CONTROL MEASURES

Protective measures shall be implemented in a fashion which reduces the risk of fatality from exposure to an oxygen deficient atmosphere to no more than 10^{-7} per hour (see Table 4). Alternate controls, such as area oxygen monitors in place of personal oxygen monitors, may be used where written justification has demonstrated that they provide an equal or superior level of safety. Since most controls are, themselves, subject to failure, their reliability must also be given appropriate consideration. For example, where a monitor-activated fan is used to reduce risk, the probability that the fan or monitor will fail must be included. An ODH control assessment should include a discussion of each of the following:

1. Environmental Controls
   - A. Ventilation
     - i) Forced
     - ii) Natural, including air makeup
   - B. Monitoring
     - i) Area oxygen monitoring
     - ii) Cryogenic systems
2. Personnel Controls
   - A. Posting
   - B. Entry control (locks, fencing, etc.)
3. Emergency Procedures
4. Special Requirements
   - A. Self-rescue supplied atmospheric respirators (escape packs)
   - B. Unusual procedures

Table 5, ODH Control Measures

ODH HAZARD CLASS	1	2
Environmental Controls		
1. Warning signs	X	X
2. Ventilation	X	X
3. Area (Fixed) Oxygen Monitoring	X (note 1, 2)	X (note 1,2)
ODH-Qualified Personnel Controls		
4. Medical approval as ODH qualified	X	X
5. ODH training	X	X
6. Personal oxygen monitor	X (note 3)	X (note 3)
7. Self-rescue supplied atmosphere respirator (escape pack)	X (note 4)	X (note 4)
8. Multiple personnel in communication		X
ODH-Restricted Personnel Controls		
9. Must not be ODH-excluded	X	X
10. ODH briefing or training	X	X
11. Personal Oxygen Monitor	X (note 3)	X (note 3)

12. Self-rescue supplied atmosphere respirator (escape pack)	X (note 4)	X (note 4)
13. One-to-one escort by ODH qualified personnel	X	X
14. At least two ODH qualified personnel		X
X = Required.		

Note 1: Area monitors are not required in spaces not intended for normal occupancy, e.g. confined spaces.

Note 2: Area monitors may be waived for temporary systems or operations at discretion of safety review panel and approval authority.

Note 3: The requirement for entrants to ODH 1 or 2 areas to carry personal oxygen monitors can be waived where it has been demonstrated that installed area (fixed) oxygen monitors provide an equal or superior level of safety (e.g., where a high background noise level makes the personal oxygen monitor alarm imperceptible). Signage at the entrance to ODH 1 and 2 areas should indicate if carrying of personal oxygen monitors by entrants is required.

Note 4: All individuals present in an ODH 1 or 2 area shall have ready access to self-rescue supplied atmosphere respirators (escape packs) unless it has been demonstrated that they do not improve the probability of surviving an oxygen deficient atmosphere (e.g., when it takes longer to put on and activate the respirator than it does to escape the oxygen deficient environment). Signage at the entrance to ODH 1 and 2 areas should indicate if carrying of self- rescue supplied atmosphere respirators (escape packs) by entrants is required.

KEY TO ODH CONTROL MEASURES

1. Warning signs - ODH signs shall be posted where they best serve to warn potentially exposed individuals. ODH signs are available from the ESH&Q Section

2. Ventilation - The minimum ventilation rate during occupancy should be established during the ODH risk assessment. This may be accomplished by any reliable means.

3. Medical approval as ODH qualified - This block of precautions shall only apply to individuals who have been classified as ODH-qualified by the Fermilab Medical Department.

4. ODH Training - Individuals shall receive training in oxygen deficiency hazards and safety measures associated with the operation. Annual retraining shall be required. Training is coordinated by the ESH&Q Section. Successful completion of an online challenge exam may be used to substitute for the annual retraining requirement.

5. Personal oxygen monitor - Individuals shall be equipped with a functioning calibrated personal oxygen monitor. Prior to each use they shall check that the displayed concentration is 21% in a normal atmosphere and the monitor is not past due for calibration. Personal oxygen monitors shall not be used beyond the last day of the month indicated on the calibration sticker. It is the responsibility of each division/section issuing personal oxygen monitors to have a program in place to insure that they are in compliance with this policy. It is the responsibility of ODH-qualified escorts to insure that the personal oxygen monitor(s) of those being escorted are not past due for calibration and are returned to the issuing organization or individual after use. Past-due monitors shall be returned to the individual or organization that issued it to arrange for recalibration.

   All personal oxygen monitors used at Fermilab are set to alarm at the mandatory confined space limit of 19.5% (see Chapter 4230). This eliminates the need to maintain two "types" of personal oxygen monitors (one for ODH and one for confined spaces) as well as the associated potential for mismatching monitor and application.

   Area oxygen monitors may be used in place of personal oxygen monitors where it has been demonstrated that they provide an equal or superior level of safety (e.g., where a high background noise level makes the personal oxygen monitor alarm imperceptible). Area ODH monitors are set to alarm at the ODH limit of 18% oxygen since there is no risk of misapplication with these fixed devices. (Alarm thresholds for area oxygen monitors may be set higher than 18% at the discretion of the division/section responsible for the ODH operation.)

Care must be exercised in the selection and use of oxygen monitors. Most instruments used in safety applications employ fuel cell type oxygen sensors. These devices consist of a diffusion barrier, a sensing electrode, a working electrode, and a basic electrolyte. The amount of current generated is proportional to the amount of oxygen consumed. There are two types of fuel cell sensors: capillary pore and membrane barrier. The former uses a narrow diameter tube through which oxygen diffuses into the sensor via capillary action. The latter depends on the partial pressure of oxygen to drive molecules through a membrane diffusion barrier into the sensor. In 2001, ES&H personnel at JLab discovered that the response of capillary type cells can be non-linear when the displacing gas is helium. The nature of this non-linearity is such that the output of the cell is higher than it should be in an oxygen-deficient atmosphere. Therefore, alarms for a capillary cell monitor may not go off until the oxygen-concentration falls below the linearly-interpolation trip point for the instrument. This observation resulted in Fermilab replacing its capillary cell monitors with membrane diffusion monitors. The non-linearity effect appears to only occur when inerting gases have a lower molecular weight than that of air.

6. Self-rescue supplied atmosphere respirator (escape pack) - All individuals present shall have ready access to self- rescue supplied atmosphere respirators (escape packs) during the operation unless it has been demonstrated that they do not improve the probability of surviving an oxygen deficient atmosphere (e.g., when it takes longer to put on and activate the respirator than it does to escape the oxygen deficient environment).

7. Multiple personnel in communication - More than one individual shall be present; all of whom shall meet requirements (3), (4), and (5) above.

8. Must not be ODH-excluded - This block of precautions shall only apply to individuals who have not been classified as ODH-excluded by the Medical Department (such individuals are classified as ODH-restricted). Individuals classified as ODH-excluded shall not participate in any ODH Class 1 or greater operation.

9. ODH briefing - Individuals shall be briefed in oxygen deficiency hazards and safety measures of the operation prior to making entry into an ODH area.

10. Self -rescue supplied atmosphere respirator - Same as (6) above.

11. One-to-one escort by ODH-qualified personnel - An escort can be provided in special cases when the persons entering an area do not meet requirements 3 and 4. Individuals shall be under the direct continuous supervision of individuals who meet (3), (4), and (5) above. Note that escorted persons shall not have been designated as ODH-excluded by the Medical Department. If not evaluated by the Medical Department, the escort assumes responsibility for judging whether or not they believe the fitness of the escorted individual would significantly impede escape from the ODH operation in the event of an alarm.

12. At least two ODH-qualified personnel - Both (7) and (11) shall be followed when making entry into an ODH area.

Example designs of ODH signs are shown in Figure 2, which follows. Actual signs should be large enough to be easily read. They shall be posted where they best serve to warn potentially exposed individuals.

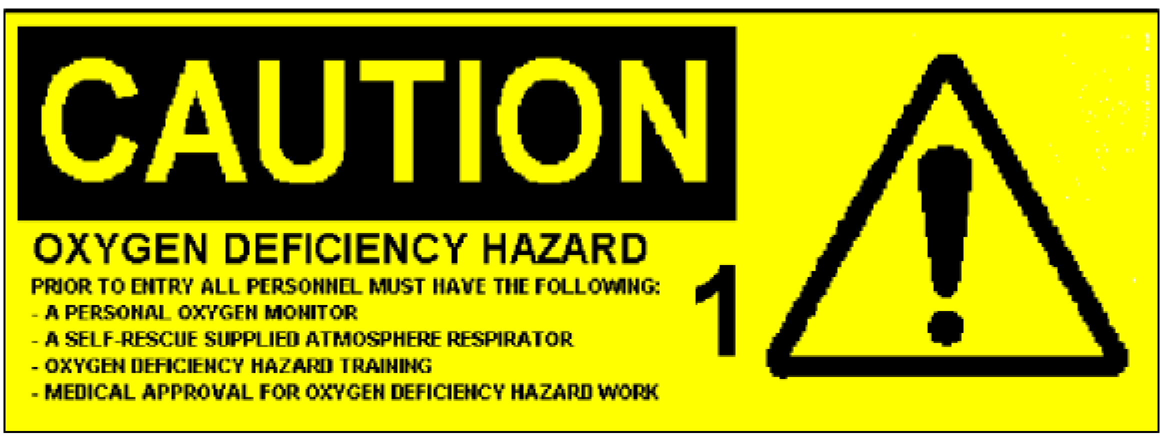


Figure 2 - ODH signs

<u>ODH Medical Surveillance</u>

Medical surveillance shall be required to assure that persons engaged in ODH operations are adequately fit to escape from an oxygen deficient situation when properly warned. Hearing, vision, cardiopulmonary function, ambulatory abilities and mental stability shall all be considered in this respect.

A three level system of medical approval shall be used which gives the greatest operational freedom to those who are most fit (Table 6). The Medical Department shall be responsible for designating the level of approval via the "Medical Approval for Restricted Activities" form. Personnel who have not been reviewed by the Medical Department are considered "ODH-restricted."

Table 6, Levels of ODH Medical Approval

LEVEL	MEANING	DURATION OF APPROVAL
ODH-Qualified	Medically qualified to participate in all ODH Class 1 or greater operations	Typically 2 years based on the age and health status of the worker
ODH-Restricted	Medically qualified to participate in ODH Class 1 and ODH Class 2 operations when properly escorted (see Table 5)	Typically 2 years based on the age and health status of the worker
ODH-Excluded	Prohibited from participation in any ODH Class 1 or greater operation	Until reclassified by the Medical Department

Procedures to Obtain ODH Medical Approval from the Medical Department

Fermilab Employees or contractors in the TRAIN database

1. Employees should contact the Medical Department to determine if a medical examination is necessary. In some instances existing health status information on file in the Medical Department is sufficiently current and complete to preclude the necessity for a pre-approval exam. In the event that an exam is needed, an appointment can be made at the time the employee contacts the Medical Department. Once an employee has been ODH-qualified, it is the responsibility of that employee to notify the Medical Department of any change in their health or medications which may affect their ODH qualification.

2. If an employee is found to be medically qualified, that information shall be entered into the TRAIN Database. In most cases, this entry will provide an adequate source of information for controlling access to ODH operations.

Non-Employees (Including Users)

1. The Fermilab representative for the non-employee shall arrange an appointment between the non-employee and the Fermilab Medical Department. If the non-employee is a contractor employee, then the representative shall notify the

Contracts Department that ODH approval is being sought.

2. The Fermilab Physician shall decide what tests need to be performed so a decision can be made regarding the non-employee's fitness for ODH work and/or SCBA use. The Fermilab Physician shall determine whether the non-employee should be ODH-qualified and/or qualified for SCBA use.

3. If the non-employee is found fit, form 5 is completed and forwarded as "distribution" indicates.

4. If the non-employee is found to be unfit for ODH work, the Medical Department will report this information to the Fermilab representative using form 5.

5. Medical approval for non-employee ODH/SCBA will expire in 2 year.

ODH Training

Individuals engaged in ODH class 1 or greater operations shall receive training in oxygen deficiency hazards and associated safety measures as outlined below. Annual retraining shall be required.

1. Normal Atmospheric Constituents
2. Effects of Exposure to Reduced Atmospheric Oxygen
    A. Reduced Abilities
    B. Loss of Consciousness
    C. Death
3. Sources and Mechanisms of Reduced Oxygen
4. ODH Safety Procedures
    A. Exposure Limit
    B. ODH Classification Scheme
    C. Required Controls
        1. Oxygen Monitors and Their Use
        2. Self-Rescue Supplied Atmosphere Respirators (escape packs)
        3. Medical Surveillance
        4. Other
    D. Evacuation and Rescue

For Lab employees, supervisors should arrange for ODH training through the ESH&Q Section. For non-employees, arrangements should be made by the Lab representative for the non-employee. "SCBA" training shall be required for all persons who must wear an SCBA (taught by the Fermilab Fire Department). A representative from the appropriate organization shall sign and date the "TRAINING" section of the "Oxygen Deficiency Hazard Approval Card."

Emergency Evacuation and Rescue

Emergency evacuation and rescue shall be conducted in accordance with the flow chart shown in

Figure 3 below. SRSAR stands for self-rescue supplied atmosphere respirator (escape pack). Individuals who have left an area due to an emergency may not re-enter until the emergency has ended and the area is known to be safe. That determination is to be made by the senior safety officer responsible for the area (or designee). Only the fire department is authorized to enter to perform a rescue. Local plans may differ slightly from that shown here.

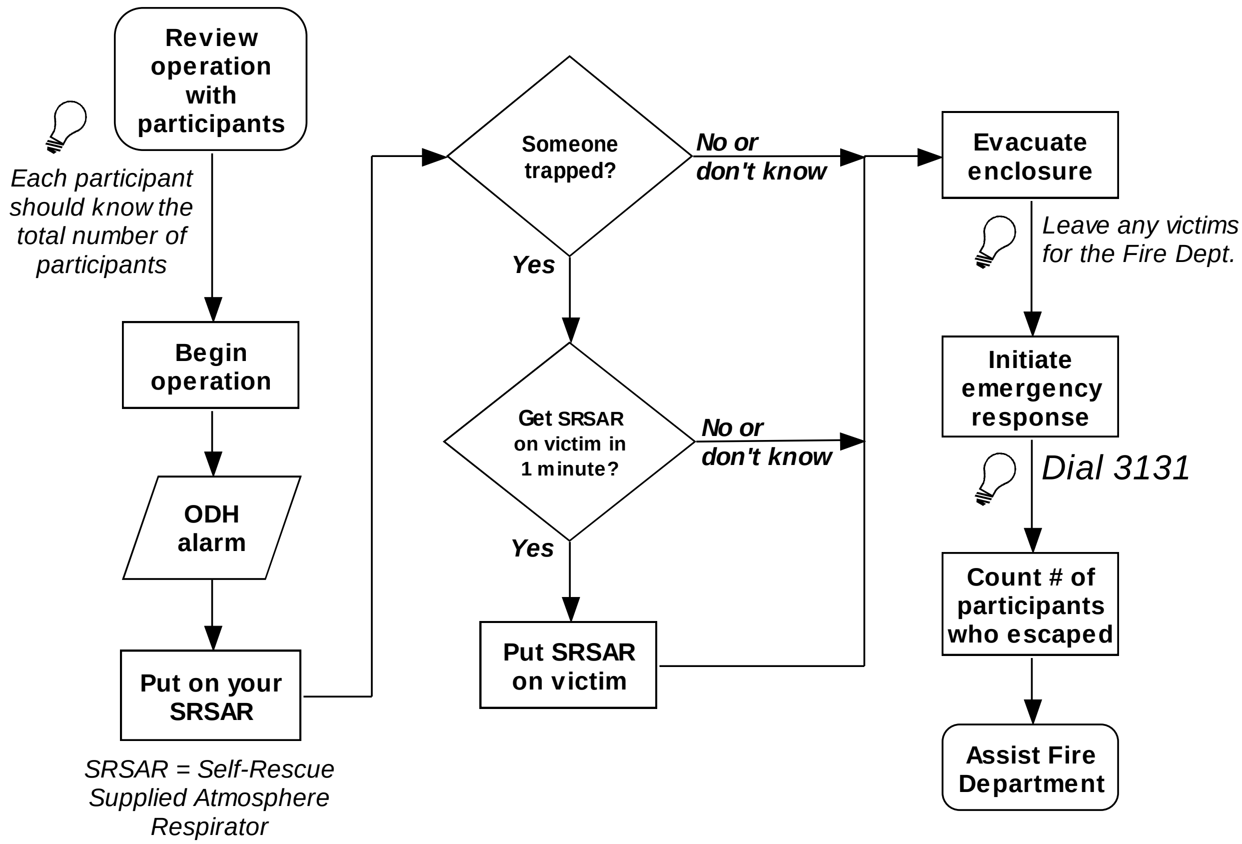


Figure 3 - Emergency evacuation and rescue flowchart

3. REFERENCE MATERIAL FOR OXYGEN DEFICIENCY HAZARDS

Effects of Exposure to Reduced Atmospheric Oxygen

Air normally contains about 21% oxygen with the remainder consisting mostly of nitrogen. (Although this section is written in terms of %O_2 at sea level, the preferred index of hazard is partial pressure of O_2. Percent O_2 is used here to maintain consistency with the "readouts" on oxygen monitors. See Safety Note 12 which is available from the ESH Section.) Individuals exposed to reduced-oxygen atmospheres may suffer a variety of harmful effects. Table 7 contains a list of some of these effects and the sea level oxygen concentrations at which they occur. At higher altitudes the same effects generally occur at greater volume concentrations since the partial pressure of oxygen is less. If exposure to reduced oxygen is terminated early enough, effects are general reversible. If not, permanent central nervous system damage or death result. Major effects hindering escape from the vicinity of an oxygen deficiency are disorientation and unconsciousness. Figure 4 is a plot of time of useful consciousness versus percent oxygen for seated individuals at sea level. For active individuals, the threshold for unconsciousness is 13%. Figure 5 shows the effect of oxygen deficiency on breathing, "error" rates, and vision.

In general, the intensities of the effects increase rapidly with falling oxygen concentration and longer exposure duration: reduced abilities, then unconsciousness, then death. While exposure to an atmosphere containing less than 17% oxygen presents some risk, it can be concluded that the 18% oxygen exposure limit provides an adequate margin of safety.

Table 7, Effect Thresholds for Exposure to Reduced Oxygen

Effect Thresholds for Exposure to Reduced Oxygen (Seated Individuals at Sea Level)	
Volume % Oxygen	Effects
17	Night vision reduced. Increased breathing volume. Accelerated heartbeat.
16	Dizziness. Time required for novel tasks doubled.
15	Impaired attention. Impaired judgment. Impaired coordination. Intermittent breathing. Rapid fatigue. Loss of muscle control.
12	Very faulty judgment. Very poor muscular coordination. Loss of consciousness. Permanent brain damage.
10	Inability to move. Nausea. Vomiting.
6	Spasmodic breathing. Convulsive movements. Death in 5 - 8 minutes.

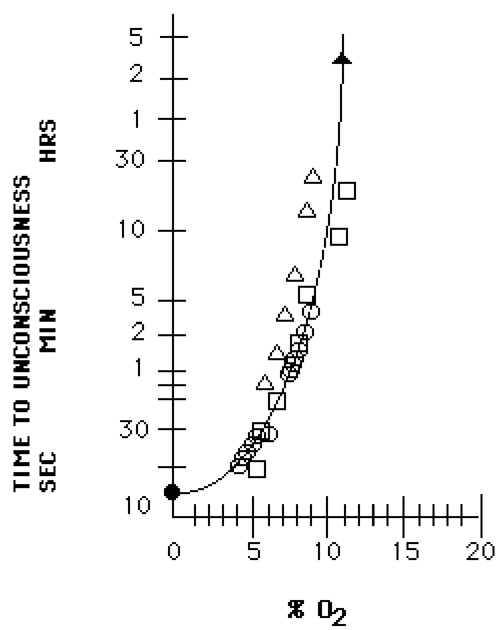


Figure 4, Time to Unconsciousness

Approximate time of useful consciousness as a function of oxygen concentration for seated subjects at sea level: Open squares and circles - duration of useful consciousness, Open triangles - time to coma, Filled triangles - threshold for unconsciousness, Filled circles - time to unconsciousness.

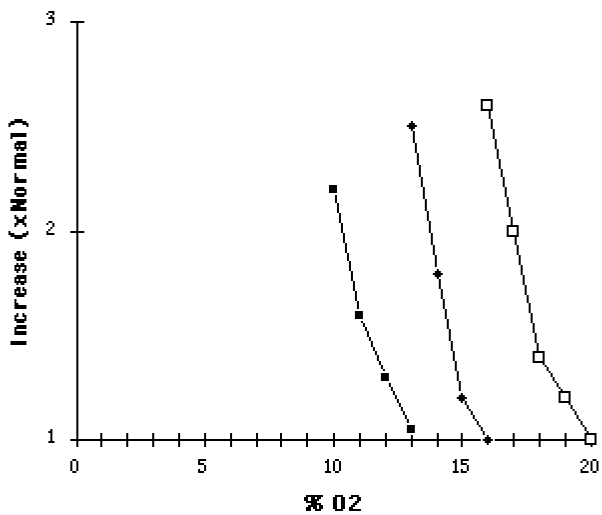


Figure 5, Other Effects of Oxygen Concentration

Other effects as a function of oxygen concentration for seated subjects at sea level: Filled squares - volume of air breathed as a function of time, Filled diamonds - error rate (inverse of test scores for judgment, memory, and discrete movements), Open squares – required minimum illumination to see the same detail

Rationale for Table 1: "Fermilab Equipment Failure Rate Estimates"

Author: B. Soyars, January 26, 2000

Failure rates reaffirmed by J. Makara, June, 2012

Table 1 in Chapter 4240 gives equipment failure rates based on Fermilab experience for a variety of systems. Rates are primarily based on data developed by the AD/Cryogenics Department. The large scale of this department's system allowed for many hours of operating time and experience. It's expected that similar systems in other departments will behave similarly. Differentiation will be made between a "leak" event and a "rupture" event.

1. Compressor (Two-stage Mycom)

The most typical ODH events related to compressors are leaking lines. A typical event is a leak in the 3/8" oil control lines for slider positioning, which leads to oil, oil mist, and helium venting within the compressor building. This has occurred about 8 times resulting in about 5 ODH alarms. It's somewhat questionable whether it was low oxygen or the presence of oil mist that set off the alarm, but since inerting gas is present in carrying the mist, assume the alarm response was real. All these events had potential for causing ODH conditions and therefore will be tallied as ODH events. Another less common reason is the opening of unvented pockets during maintenance. This has happened perhaps twice. It's possible that compressor building ODH events could be under-reported since these non-cryogenic events typically have little or no impact on accelerator operations. Thus, it seems plausible to increase the leak event total number by 50%, from 10 to 15. There have been through January 1999 125,000 hours with the He header system live and compressors operating. Then, for leaks:

$$\text{failure rate} = \frac{15}{\left(1.25\times10^{5}\ \text{hr}\right)\times 25\,\text{cmprs}} = 5\times10^{-6}\ /\text{hr}$$

A similar number for rupture is more difficult to determine since no real rupture events have been recorded. Nevertheless, by assuming one rupture failure, an upper limit to this failure rate can be estimated:

$$\text{failure rate} = \frac{1}{\left(1.25\times10^{5}\ \text{hr}\right)\times 25\,\text{cmprs}} = 3\times10^{-7}\ /\text{hr}$$

2. Dewar

A wide variety of dewars are operated at Fermilab and much dewar experience has been gained. (Note, information outside of AD/Cryogenics will be considered here). A typical major failure mode is when the insulating vacuum shell gets cracked leading to the loss of vacuum to air and the potential for significant venting of warmed-up cryogens. Consider a failure that occurred at MTF (January 1997) in which a 10,000 gal nitrogen dewar had its vacuum shell cracked due to cold shocking. This occurred after 5.5 years of it being in service. This was the only failure over this time period for an assumed average of 20 dewars in continuous service. Take this 5.5 years as typical mean time between failure for a lot of 20 dewars. Then the failure rate would be:

$$\text{failure rate} = \frac{1}{\left(4.8\times10^{4}\ \text{hr}\right)\times 20\ \text{dewars}} = 1\times10^{-6}\ /\text{hr}$$

This predicted value rate matches what was originally used in Table 1, indicating that it seems to be a fair value to use for dewar failure rates. Further laboratory experience can be considered in a more anecdotal fashion. A few other similar failures have occurred during the 30 year lab history. About two more cold shock failures have occurred, and about two more 500 liter portable dewars have lost vacuum (one at Lab 2 when dropped from a truck, another in the Village). Consider then five failures for 20 dewars in continuous service during a 30 year period. This produces a failure rate identical to the above calculation. This supports the above analysis being indeed typical.

3. Electrical Power Failure

The original Table 1 gives this failure rate as 1 E-4 /hr, and 3 E-4 /demand.

This existing time failure rate comes out to about 1 per year, which is in agreement with experience.

4. Fluid line (Cryogenic)

Assume this category includes fittings, valves, seals, and O-rings. Failures of this nature have been the most commonly encountered cause for AD/Cryogenics ODH events. An example is temperature related seal failures. AD/Cryogenics data has estimated about 30 total ODH events from 1983-1988, and <15 events from 1989-1996. Since we have documented 16 tunnel spill events, let's assume there have been about 30 of the 45 total events falling into this category of cryogenic fluid lines.

Through January 1999 there were 105,000 Tevatron cryogenic system hours cold. Assume 24 refrigerator buildings each with 25 fittings (bayonets and reliefs). Then the leak failure rate for a fluid line or fitting is:

$$105{,}000 \text{ hrs} \times 24 \text{ bldgs} \times 25 \text{ ftg/bldg} = 63 \times 10^{6} \text{ ftg-hrs}$$

$$\text{failure rate} = \frac{30}{63 \times 10^{6}} = 5 \times 10^{-7} \text{ /hr}$$

Rupture failures, such as a bayonet blowing out, are more difficult to determine since no real rupture events have been recorded. Nevertheless, by assuming one rupture failure, an upper limit to this failure rate can be estimated:

$$\text{failure rate} = \frac{1}{\left(63 \times 10^{6} \text{ hr}\right)} = 2 \times 10^{-8} \text{ /hr}$$

5A. Magnet (cryogenic)

Let's look at magnets under two separate conditions. First consider cold and powered magnets. Personnel are not working near the magnets under these circumstances. Up to January 1999, there have been 63,000 hours of Tevatron system powered conditions. There have been 11 magnet spill events mostly, if not all, due to single-phase rupture to vacuum from an electrical fault. Then magnet "powered, unmanned" failure rate is:

$$\text{failure rate} = \frac{11}{63000 \times 1000 \text{ magnets}} = 2 \times 10^{-7} \text{ /hr}$$

5B. Magnet (unpowered, could be cryogenic conditions, could be warm)

A separate condition for the magnets are when they are not powered. This assumes that manned activity is occurring around the magnets which either are cold, or are warm with inerting gases present. These conditions have produced 2 potential ODH events. Both of these recorded failures were magnet Kautzky valves getting hit. In fact, the valves remained intact and no spill occurred; but nonetheless, since there was potential, these have been counted as ODH events. There have been 89,000 hours of Tevatron system not powered. Then magnet "not powered, manned" failure rate is:

$$\text{failure rate} = \frac{2}{89000 \times 1000 \text{ magnets}} = 2 \times 10^{-8} \text{ /hr}$$

6. Header Piping Assembly

Three ODH events were observed that were related to the helium header piping. The failure rate will be based on failures per vulnerable or accessible assembly. In these failure cases, the vulnerable assembly was a flex hose attached to the header. Note that two of these were the failures discussed in 5B, which could have led to exposure of either the header or the magnet inventory (or both). Therefore, those events will be counted in both categories. One additional event involved the header opening up during a magnet change when an incorrect maintenance procedure let an uncapped Kautzky valve leak when its control pressure line was broken. For the header in the Tevatron, there are about 70 flex hose connections to the header for one house. From the known header operating time of about 125,000 hours, we get a failure rate per piping assembly:

$$\text{failure rate} = \frac{3}{125000 \times 70 \times 24} = 1 \times 10^{-8} \text{ /hr}$$

7. U-Tube change

Procedures reduce the ODH impact of problems during U-tube changes by minimizing the exposure to large sources. For example, isolation valves are closed and the system depressurized before the pull. So when problems or failures have occurred, they have procedurally been prevented from falling into the ODH event category. Thus, AD/Cryogenics doesn't really offer any ODH statistics for altering the original 4240 failure rate estimates (3 x 10^{-2}/D small event, 1 x 10^{-3}/D large event).

REFERENCES:

1. Tevatron Tunnel ODH Spill Analysis, W. Soyars and J. Theilacker, February 22, 1999.

2. ODH Statistics, J. Theilacker, October 3, 1988.

3. Discussion of Known ODH Events, W. Soyars, April 18, 1996.

4. Email from Tom Peterson, "Dewar Failure Rates," January 26, 2000.

4. STANDBY EQUIPMENT FAILURE ON DEMAND AND SAMPLE CALCULATIONS

Failure on Demand Rates for Standby Ventilation Equipment

10/20/2014

R. Schmitt

Introduction

ODH analyses at Fermilab frequently rely on standby ventilation systems. The reliability of any standby system depends on the test period. This calculation shows the probability of a failure on demand for fans and motorized louvers. The equations are from David Smith, Reliability, Maintainability and Risk, and it assumes that the units are unavailable for half of the test period.

Some buildings have multiple fans which are all be requested to start during an event. There is a probability that all fans start and their combined flow rate along with the leak rate determines the oxygen concentration. There is another probablility that some fans will fail to start. If less than the full number of fans is running, then the ventilation and resulting oxygen concentration would be lower. The same situation exists for motorized louvers.

Nomenclature

- λ.fan is the probability of a fan failing while running continuously.
- λ.louver is the probability of a motorized louver failing while running continuously
- Test.period is the time between operational tests
- n is the number of fans installed
- m is the number of fans starting
- F.FOD.fan.1o1 is the failure on demand for one fan where one is installed
- F.FOD.fan.1o2 is the failure on demand for one fan starting where two are installed
- F.FOD.fan 1o3 is the failure on demand for one fan starting where three are installed

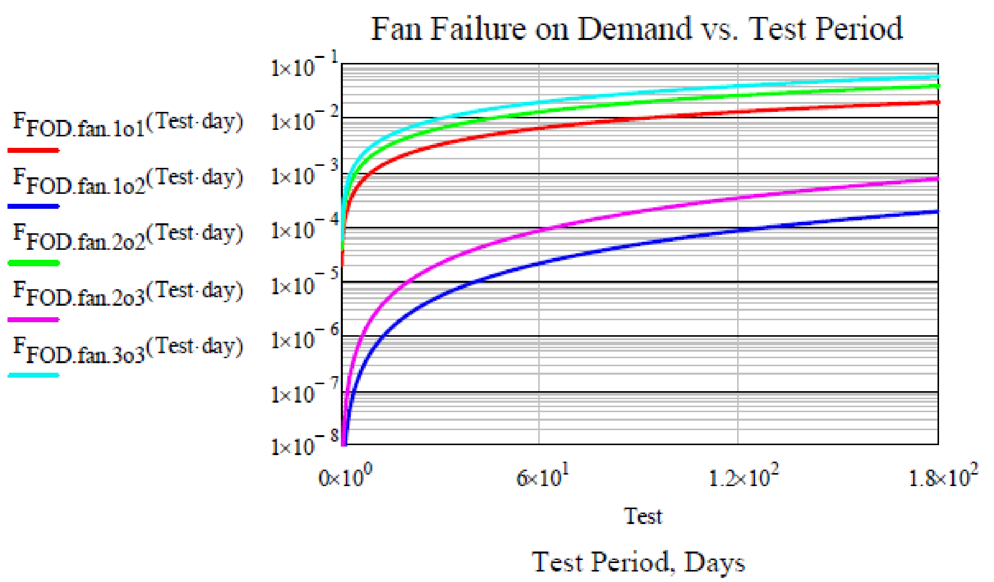
Failure on demand calculation for standby fans or louvers

$$F_{FOD}(m,n) = \frac{\left(\frac{Test_{period}}{2}\cdot\lambda\cdot m\right)^{n+1-m}}{(n+1-m)!}$$

Failure on Demand with 'm' units starting out of 'n' units installed

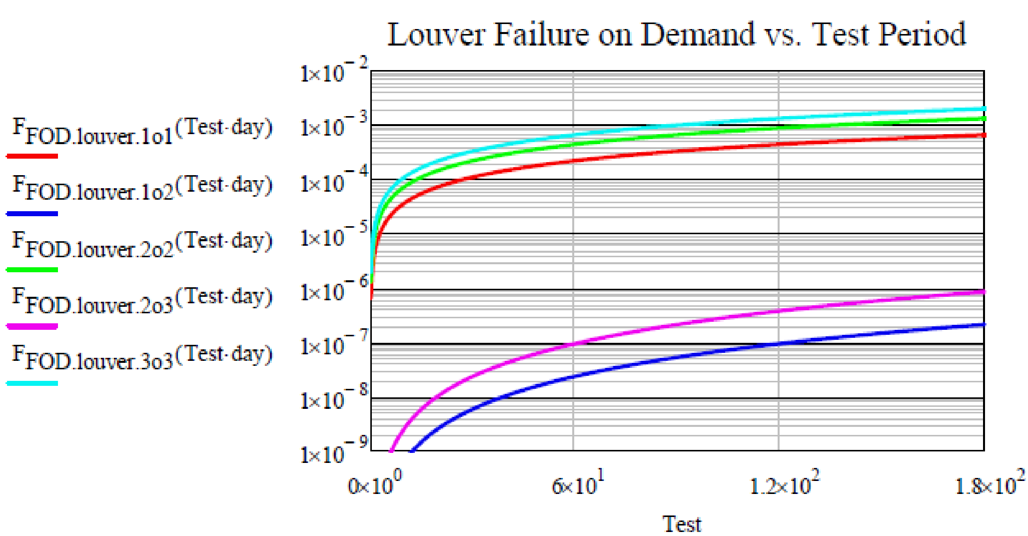
Fan Failure on Demand Chart

$\lambda_{fan} = 9 \times 10^{-6} \cdot \frac{1}{hr}$ fan failure rate including motor, starter and fuses. Not including power supply



Motorized Louver Failure on Demand chart

$\lambda_{louver} = 3 \times 10^{-7} \cdot \frac{1}{hr}$ louver failure rate including motor, starter and fuses. Not including power supply



Reference

David Smith, Reliability, Maintainability and Risk, page 95, for system unavailability with standby units. Table 8.6. These equations assume that the equipment is unavailable for half of the test period.

8.1.4 Systems with cold standby units and repair

Cold standby implies that the redundant units, when not required, are not in use and thus have zero failure rate. Similar logic can be applied to derive expressions for standby scenarios whereby one redundant unit is not activated until needed. A zero failure rate in the dormant state is assumed.

In this case the failure rate becomes $(n - 1)\,\lambda$ because only $m - 1$ are available to fail. The failure rate for the second failure is the same because the standby unit has been activated and is thus $(n - 1)\,\lambda$. Thus the probability of the second failure is $(n - 1)\,\lambda$. unit down time. The system failure rate is thus:

$$(n - 1)^2 \lambda^2 \mathbf{MDT}_{\mathbf{unit}}$$

This leads to Table 8.6 for the system unavailabilities.

MDT= mean down time= $\frac{T}{2}$

T=test period

λ = operating failure rate

Table 8.6 System unavailability (up to 3 units in standby, i.e. $n = 4$, $m = 1$)

Number of units, n				
1	λ MDT			
2	λ^2 MDT$^2/2$	2λ MDT		
3	λ^3 MDT$^3/6$	$2\lambda^2$ MDT^2	3λ MDT	
4	λ^4 MDT$^4/24$	$4\lambda^3$ MDT$^3/3$	$9\lambda^2$ MDT$^2/2$	4λ MDT
	1	2	3	4
	Number required to operate, m			

repair time could be added to T

ODH Fatality Rate Calculation examples with active ventilation or valve controls

R. Schmitt

10/20/2014

Introduction

The use of cryogens can create an oxygen deficient environment through equipment failures or leaks. To mitigate the risk of these failures, ventilation fans and detection monitors are commonly installed. These safety features help detect low oxygen concentrations and provide fresh air. However the ventilation and detectors can also fail to operate when needed. Performing ODH fatality rate calculations for ventilation scenarios requires all situations to be accounted for that can put people at risk. Three scenarios that may occur are as follows:

1. ODH condition with no leaks and ventilation/monitors are working properly
2. ODH condition with a gas/cryogen leak and ventilation/monitors are working properly
3. ODH condition with a gas/cryogen leak and ventilation/monitors fail to operate

General Procedure for ODH calculations with active ventilation or controls

1. Establish a list of all pieces of equipment and credible failure modes that could occur and produce an oxygen deficient environment

2. Determine the probability of failure for each leak from tables 1, 2 and 3 in FESHM 4240

3. Calculate the fatality factor for each specific failure
   - Determine the leak rate of the inert gas into the environment
   - Determine the oxygen concentration using the ventilation rate and the leak rate into the environment with the proper equation in FESHM 5064
   - Determine the Fatality Factor from FESHM 4240 Technical Appendix,figure 1.

4. If applicable determine the ventilation failure rate.

5. Calculate the fatality rate for each leak. For simple systems this is simply the product of the leak probability times the fatality factor. For systems with active ventilation components the ventilation failure rate must be factored in with the leak rate and fatality factors as shown in the examples below.

6. Sum the fatality rate for all credible leaks to obtain an overall building fatality rate

Symbols and Terminology

This example is written in Mathcad. Equals is written as = or :=

Fatality Factor Calculation Example

$\text{Release}_1 := 100\,\frac{ft^3}{min}$ leak rate of inert gas into a volume, cubic feet per minute

$Q_{fan.1} := 300\,\frac{ft^3}{min}$ ventilation rate with one fan, cubic feet per minute

$Q_{fan.2} := 600\,\frac{ft^3}{min}$ ventilation rate with two fans, cubic feet per minute

$$\text{FatalityFactor}(FO2) := \left| \begin{array}{l} PO2 \leftarrow \frac{FO2 \cdot 135}{.180} \\ out \leftarrow \left| \begin{array}{ll} 1.0 & \text{if } PO2 \le 65 \\ 0 & \text{if } PO2 > 135 \\ 10^{6.5 - \frac{PO2}{10}} & \text{otherwise} \end{array} \right. \\ out \end{array} \right.$$

This equation calculates the Fatality Factor, which can also be found on the chart in FESHM 4240, Figure 1.

This equation is referenced later in the examples.

The Fatality Factor is unitless.

$$C_{fan1} := 0.21 \cdot \left(1 - \frac{\text{Release}_1}{Q_{fan.1}}\right) = 0.14$$

$$C_{fan2} := 0.21 \cdot \left(1 - \frac{\text{Release}_1}{Q_{fan.2}}\right) = 0.175$$

FESHM 4240 Case C, determines the fraction oxygen concentration for a fan drawing contaminated air from the building.

$\text{FatalityFactor}(C_{fan1}) = 10 \times 10^{-5}$ Fatality factor with one fan running

$\text{FatalityFactor}(C_{fan2}) = 2.371 \times 10^{-7}$ Fatality factor with two fans running

Fatality Rate Calculations with Active Ventilation

Failure probabilities and fatality factors are for example only. Equipment failure rates and credible leak rates must be determined before this fatality rate calculation. For fans and louvers, 1o2 nomenclature refers to one operates out of two installed, for example. Three examples follow:

Simple system with one possible leak and one standby fan

Equipment failure rates

$P_{leak} := 1 \cdot 10^{-8} \cdot \frac{1}{hr}$ Probablility of a leak, per hour, found in FESHM tables 1,2 or 3

$P_{F.FR} := \frac{9 \cdot 10^{-6}}{hr}$ Probability of fan failure rate per hour while running, including motor, starter and fuses. Not including power. Found in FESHM 4240 tables or Appendix

$P_{F.FOD} := 7.6 \cdot 10^{-4}$ Probablility of a single standby fan failure on demand, unitless

$P_{ODH.FOD} := 4.86 \cdot 10^{-3}$ Probability of ODH alarm system failure on demand, unitless

$P_{power.failure} := 1 \cdot 10^{-4} \cdot \frac{1}{hr}$ Probability of power failure, per hour, per FESHM 4240, table 1

Standby Fan system failure on demand

$$P_{vent.FOD} := P_{F.FOD} + P_{ODH.FOD} = 5.62 \times 10^{-3}$$

Probablility of leak occuring and fan system fails on demand or power fails

P1 is the probablility of a leak occuring and the standby ventilation does not start or power fails

$$P_1 := \left[P_{leak} \cdot hr \cdot \left(P_{vent.FOD} + P_{power.failure} \cdot hr\right) \cdot \frac{1}{hr}\right] = 5.72 \times 10^{-11} \cdot \frac{1}{hr}$$

P2 is for the leak occuring, the ventilation starting then failing while running or power fails

$$P_2 := \left[P_{leak} \cdot hr \cdot \left[\left(1 - P_{vent.FOD}\right) \cdot P_{F.FR} \cdot hr + P_{power.failure} \cdot hr\right] \cdot \frac{1}{hr}\right] = 1.089 \times 10^{-12} \cdot \frac{1}{hr}$$

P3 is the probablility of a leak occuring and ventilation not running

$$P_3 := P_1 + P_2 = 5.829 \times 10^{-11} \cdot \frac{1}{hr}$$

P4 is the probablility of a leak occuring and the ventilation starting and running

$$P_4 := \left(P_{leak} - P_3\right) = 9.942 \times 10^{-9} \cdot \frac{1}{hr}$$

Fatality Factors are based on the expected oxygen concentration

$$FF_{leak.no.fan} := 1$$

$$FF_{leak.one.fan} := \text{FatalityFactor}\left(C_{fan1}\right) = 10 \times 10^{-5}$$

Fatality Rate for this leak

The fatality rate is a product of the condition probablity and the associated fatality factor.

$$FR_{leak2} := P_3 \cdot FF_{leak.no.fan} + P_4 \cdot FF_{leak.one.fan} = 5.928 \times 10^{-11} \cdot \frac{1}{hr}$$

which can also be written as

$$FR_{leak} := \begin{pmatrix} P_3 & P_4 \end{pmatrix} \cdot \begin{pmatrix} FF_{leak.no.fan} \\ FF_{leak.one.fan} \end{pmatrix} = 5.928 \times 10^{-11} \cdot \frac{1}{hr}$$

System with one possible leak and two standby fans

Equipment failure rates

$P_{leak} = 1 \times 10^{-8} \cdot \frac{1}{hr}$ Probablility of a leak

$P_{F.FR} = 9 \times 10^{-6} \cdot \frac{1}{hr}$ probability of fan failure rate while running, including motor, starter and fuses. Not including power

$P_{F.FOD.1o2} := 2.9 \cdot 10^{-7}$ probablility of one fan, 1o2, failure on demand

$P_{F.FOD.2o2} := 1.5 \cdot 10^{-3}$ probablility of both fans, 2o2, standby fan failure on demand

$P_{ODH.FOD} = 4.86 \times 10^{-3}$ Probability of ODH alarm system failure on demand

$P_{power.failure} = 1 \times 10^{-4} \cdot \frac{1}{hr}$ Probability of power failure

Standby Fan system failure on demand

$$P_{vent.FOD.1o2} := P_{F.FOD.1o2} + P_{ODH.FOD} = 4.86 \times 10^{-3}$$

$$P_{vent.FOD.2o2} := P_{F.FOD.2o2} + P_{ODH.FOD} = 6.36 \times 10^{-3}$$

Probablility of leak occuring & fan system fails on demand or power fails

P10 is the probability of a leak occuring and one fan fails

$$P_{10} := \left[P_{leak} \cdot hr \cdot \left(P_{vent.FOD.1o2} + P_{power.failure} \cdot hr \right) \cdot \frac{1}{hr} \right] = 4.96 \times 10^{-11} \cdot \frac{1}{hr}$$

P11 is for the leak occuring, the ventilation starting then failing while running or power fails

$$P_{11} := \left[P_{leak} \cdot hr \cdot \left[\left(1 - P_{vent.FOD.1o2} \right) \cdot P_{F.FR} \cdot hr + P_{power.failure} \cdot hr \right] \cdot \frac{1}{hr} \right] = 1.09 \times 10^{-12} \cdot \frac{1}{hr}$$

P12 is the probability of a leak occuring and one fan not starting or running

$P_{12} := P_{10} + P_{11} = 5.069 \times 10^{-11} \cdot \frac{1}{hr}$

P13 is the probablility of a leak occuring and the both fans fail or power fails

$P_{13} := \left[P_{leak} \cdot hr \cdot \left(P_{vent.FOD.2o2} + P_{power.failure} \cdot hr\right) \cdot \frac{1}{hr}\right] = 1.794 \times 10^{-} \; P_{13} = 6.46 \times 10^{-11} \cdot \frac{1}{hr}$

P14 is the probability of a leak occuring and both fans start then both fail while running

$P_{14} := \left[P_{leak} \cdot hr \cdot \left[\left(1 - P_{vent.FOD.2o2}\right) \cdot P_{F.FR} \cdot 2 \cdot hr + P_{power.failure} \cdot hr\right]\right] \cdot \frac{1}{hr} = 1.179 \times 10^{-12} \cdot \frac{1}{hr}$

P15 is the probablility of a leak occuring and ventilation not running

$P_{15} := P_{13} + P_{14} = 6.578 \times 10^{-11} \cdot \frac{1}{hr}$

P16 is the probablility of a leak occuring and all ventilation starting and running

$P_{16} := \left(P_{leak} - P_{12} - P_{15}\right) = 9.884 \times 10^{-9} \cdot \frac{1}{hr}$

Fatality Factors are based on the expected oxygen concentration

$FF_{leak.no.fan} = 1$

$FF_{leak.one.fan.} := FatalityFactor\left(C_{fan1}\right) = 10 \times 10^{-5}$

$FF_{leak.two.fans} := FatalityFactor\left(C_{fan2}\right) = 2.371 \times 10^{-7}$

Fatality Rate for the leak

The fatality rate is a product of the condition probablities and the associated fatality factors.

$FR_{leak.2.fan.system} := P_{14} \cdot FF_{leak.no.fan} + P_{12} \cdot FF_{leak.one.fan} + P_{16} \cdot FF_{leak.two.fans}$

$FR_{leak.2.fan.system} = 1.186 \times 10^{-12} \cdot \frac{1}{hr}$

$$FR_{leak.2fan.system} := \begin{pmatrix} P_{14} & P_{12} & P_{16} \end{pmatrix} \cdot \begin{pmatrix} FF_{leak.no.fan} \\ FF_{leak.one.fan} \\ FF_{leak.two.fans} \end{pmatrix} = 1.186 \times 10^{-12} \cdot \frac{1}{hr}$$

System with a continuous leak, constant fan and standby shutoff valve

In this example the fan failure may be detected by an air flow switch or oxygen sensor, which would then be interlocked with the gas supply shutoff valve. The example shows the calculation procedure only, equipment failure rates should be determined elsewhere.

Equipment failure rates

$P_{leak.continuous} := 1$	Probablility of a leak
$P_{F.FR} = 9 \times 10^{-6} \cdot \frac{1}{hr}$	probability of fan failure rate while running, including motor, starter and fuses. Not including power
$P_{SOV.FOD} := 1 \cdot 10^{-3}$	probablity of a solenoid valve failing to operate
$P_{ODH.FOD} = 4.86 \times 10^{-3}$	Probability of ODH alarm system failure on demand
$P_{power.failure} = 1 \times 10^{-4} \cdot \frac{1}{hr}$	Probability of power failure

Gas shutoff system failure on demand

$$P_{shutoff.FOD} := P_{SOV.FOD} + P_{ODH.FOD} = 5.86 \times 10^{-3}$$

Probablility of ventilation stopping and shutoff system failing

P20 is the probability of ventilation failing due to fan failure or power outage

$$P_{20} := \left[\left(P_{F.FR} \cdot hr + P_{power.failure} \cdot hr \right) \cdot \frac{1}{hr} \right] = 1.09 \times 10^{-4} \cdot \frac{1}{hr}$$

P21 is for ventilation stopping and the shutoff system not operating

$$P_{21} := \left[P_{20} \cdot hr \cdot \left(P_{shutoff.FOD} \right) \cdot \frac{1}{hr} \right] = 6.387 \times 10^{-7} \cdot \frac{1}{hr}$$

Fatality Factors are based on the expected oxygen concentration

$$FF_{fan.on} := 0$$

$$FF_{fan.stops.gason} := 1$$

Fatality Rate for the leak

The fatality rate is a product of the condition probablity and the associated fatality factor.

$$FR_{leak.continuous} := P_{21} \cdot FF_{fan.stops.gason} = 6.387 \times 10^{-7} \cdot \frac{1}{hr}$$